

Collective flow in small systems

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Abstract

The large density of matter in the interaction region of the proton-nucleus or deuteron-nucleus collisions enables the collective expansion of the fireball. Predictions of the hydrodynamic model for the asymmetric transverse flow are presented and compared to experimental data.

Keywords: collective flow, hydrodynamic model, ultrarelativistic collisions

1. Introduction

The bulk dynamics of the fireball created in ultrarelativistic heavy-ion collisions is governed by hydrodynamics. Pressure gradients in the transverse plane lead to a rapid transverse expansion. The azimuthal asymmetry of particle spectra can be quantified with the flow coefficients v_n . Inspection of the initial conditions in the high energy p-A or d-A collisions shows that collective flow should appear in such systems [1]. Alternatively, saturation phenomena yield qualitatively similar angular correlations for the emitted particles [2]. We present a selection of results obtained from the hydrodynamic model in comparison to recent experimental data for p-Pb collisions at the LHC [3, 4, 5] and d-Au collisions at RHIC [6].

2. The fireball

The multiplicity in p-Pb collisions at $\sqrt{s} = 5.02\text{TeV}$ reaches values comparable to those in peripheral Pb-Pb collisions at 2.76TeV. It means that in the most violent p-Pb interactions the energy deposited in the interaction region is similar as in heavy-ion collisions. The size of the interaction region can be estimated in models of the initial state, e.g., the Glauber Monte Carlo model or the IP-glasma model [1, 7, 8]. The size of the fireball in p-Pb collisions is smaller than in peripheral Pb-Pb collisions, which means that the energy density in the center of the fireball is high and, consequently, the pressure gradients can generate a rapid transverse expansion. From the Glauber Monte Carlo model [9] of p-Pb interactions one finds that the number of participant nucleons goes beyond 20 for the most violent collisions. Additional fluctuations of the energy deposition in each individual nucleon-nucleon interaction increase the range of the energies of the fireball. In fact, a simple model which convolutes the distribution of the participant nucleons with a negative binomial distribution of particles emitted per nucleon-nucleon collision reproduces the observed distribution of the charged tracks in p-Pb collisions [7]. Event by event fluctuations in the

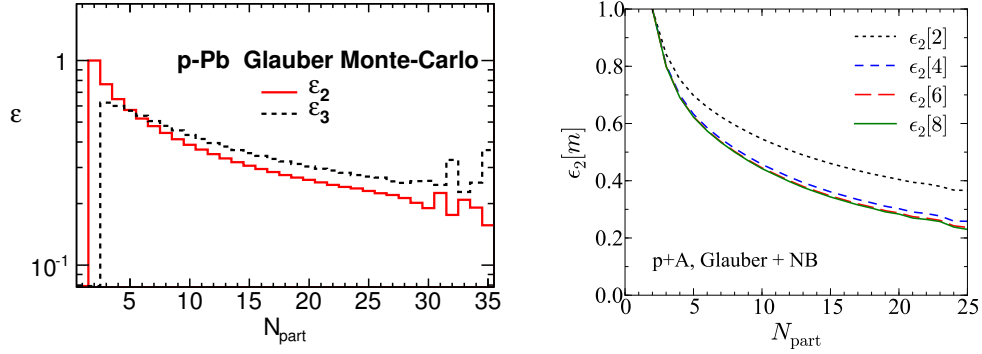


Figure 1. (left) Initial eccentricity and triangularity for p-Pb collisions as functions of the number of participant nucleons [1]. (right) Initial eccentricity in p-Pb collisions from higher order cumulants [10].

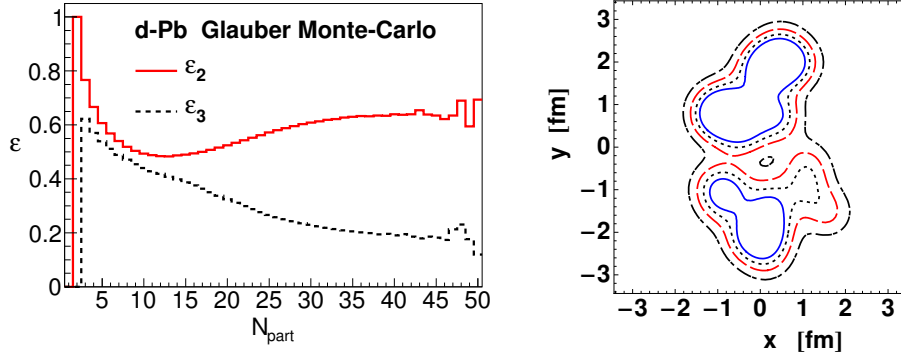


Figure 2. (left) Initial eccentricity and triangularity for d-Pb collisions as functions of the number of participant nucleons. (right) Initial entropy density in the transverse plane for a typical d-Pb event [1].

distribution of the participant nucleons in the transverse plane and in the energy deposition yield nonzero initial eccentricities ϵ_n of the fireball

$$\epsilon_n e^{in\Psi_n} = - \frac{\int r^{n+1} e^{in\phi} \rho(r, \phi) dr d\phi}{\int r^{n+1} \rho(r, \phi) dr d\phi}. \quad (1)$$

In p-Pb interactions ϵ_2 and ϵ_3 originate solely from the shape fluctuations of the fireball. These eccentricities decrease with the number of sources (left panel of Fig. 1). Still, the values of ϵ_n for the highest multiplicity collisions, where the hydrodynamic expansion takes place, are sizable, hence the resulting v_2 and v_3 can be measured. The contributions from fluctuations and from the average asymmetry to the eccentricity can be separated using multiparticle cumulant measures for the flow coefficients [11]. In the limit of a large number of sources the higher order cumulants should vanish, as they measure the shape asymmetry. Since in p-Pb collisions the number of participant nucleons is limited, the Glauber Monte Carlo model gives a nonzero value of the higher order cumulants ϵ_n (right panel of Fig. 1) [10, 12], with the elliptic and triangular flow coefficients following approximately the relation $v_n\{2\} > v_n\{4\} \simeq v_n\{6\} \simeq v_n\{8\}$, as observed experimentally [13].

When a deuteron hits a large nucleus side-wise, the azimuthal asymmetry is large due to the deformation of the intrinsic wave function of the deuteron [1]. The shape of the fireball in the transverse plane reflects the large eccentricity of the density profile (right panel of Fig. 2). By triggering on events with a large number of participant nucleons, configurations with a large ϵ_2 are selected (left panel of Fig. 2). The same argument applies to tritium-Au or ^3He -Au collisions [14, 15]. High multiplicity events correspond to configurations where the smaller nucleus hits the larger nucleus with a large separation between the three nucleons, resulting in large triangularity. The ^{12}C nucleus exhibits strong nuclear correlations, as it consists of three α -like clusters. The fireball formed in high multiplicity collisions

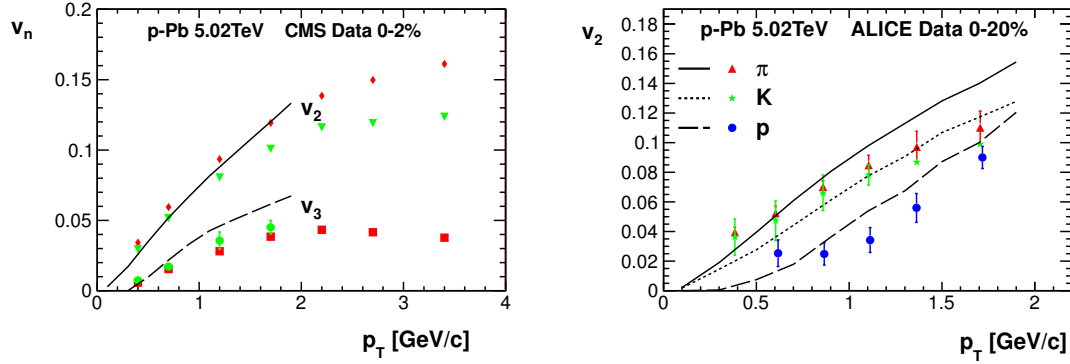


Figure 3. (left) Elliptic and triangular flow coefficients of charged particles in p-Pb collisions from the hydrodynamic model compared to the CMS data [17]. (right) Elliptic flow coefficient of identified particles from the hydrodynamic model compared to the ALICE data [18].

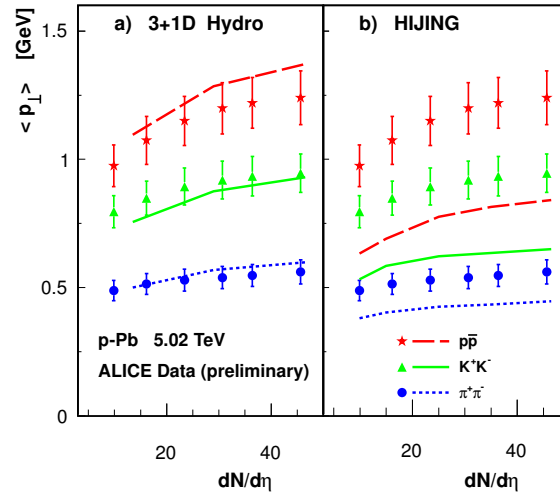


Figure 4. Average transverse momentum of identified particles in p-Pb collisions, data from ALICE Collaboration [19], compared to the results of the HIJING model and of the viscous hydrodynamics.

of such nuclei with a large target nucleus exhibits significant geometric triangularity that should be observable as an increase of the triangular flow for the highest multiplicity events [16].

3. Results of the hydrodynamic model

The expansion of the fireball is described using 3+1-dimensional viscous hydrodynamic simulations with shear and bulk viscosity [20]. At the freeze-out temperature of 150 MeV, hadrons are emitted statistically and resonance decays are accounted for [21]. The main source of uncertainty in the model calculations resides in the assumptions on the initial conditions. The details of the hydrodynamic stage involve additional parameter dependence. Nevertheless, most of the calculations predict flow coefficients consistent with experiment [7, 22, 15, 23, 24, 25], with the exception of the calculation using IP-glasma initial conditions [26].

The resulting elliptic and triangular flow coefficients for charged particles are shown in Fig. 3. The calculation describes reasonably well the measured flow asymmetry. The observed elliptic and triangular flow in p-Pb collisions is similar as in peripheral Pb-Pb collisions, suggesting a common origin. Hydrodynamic calculations in the two systems explain uniformly these observations via formation of the collective flow. We note that the presence of nonzero harmonic flow coefficients generates ridge-like structures in the two particle correlation function in the relative azimuthal

angle and pseudorapidity [27]. The elliptic flow in p-Pb collisions for identified particles shows a splitting between particles of different mass (Fig. 3 right panel). This behavior arises naturally in the framework of the hydrodynamic model [28]. A strong elliptic flow is observed in d-Au collisions at RHIC energies [6], consistent with earlier predictions of the hydrodynamic model. The presence of the collective transverse flow increases the average transverse momentum of the emitted particles. The transverse momentum of particles emitted in p-Pb collisions is larger than in models consisting of a convolution of nucleon-nucleon collisions (Fig. 4 right panel) [29]. The hydrodynamic model predicts a larger transverse flow for heavier particles (Fig. 4 left panel) [28] and thus explains the mass hierarchy observed experimentally. For the asymmetric p-Pb or d-Au collisions, the hydrodynamic model predicts stronger collectivity, i.e. larger v_n and larger transverse momenta, on the nucleus-going side.

4. Conclusions

The high energy density in the fireball created in high-multiplicity p-Pb or d-Au collisions at ultrarelativistic energies implies the possibility of a collective expansion of such a small system. Hydrodynamic calculations are in semi-quantitative agreement with experimental measurements of the harmonic flow coefficients and the average transverse momenta of emitted particles.

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